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Nanocrystalline Iron-Cobalt Alloys for High saturation Indutance

Conrad Williams
MORGAN STATE UNIVERSITY (INC)
1700 E COLD SPRING LN
BALTIMORE, MD 21251-0002

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14. ABSTRACT

A Single Domain Wall in a Magnetic Toroidal Cylinder

One of the major questions driving the research at Morgan State University is “Can one achieve high magnetization (B > 1.7 T) at low fields (H < 1 mT) in iron-cobalt polycrystalline materials, to improve the efficiency of transformers and other related devices?” Nanocrystalline cobalt-iron could be a good possibility if the anisotropy at the grain boundaries were overcome and the goal of B > 1.7 T) could be reached at low fields. Such an achievement would greatly enhance the efficiency of the power transfer in these devices. A new principle has been found theoretically at Morgan State University that suppresses anisotropy using the geometry of the thin toroid. We have shown experimentally that the thin film toroid calculations may be applicable to up to millimeter toroids. These results open a wide range of possibilities for the development of low energy-high efficiency transformers that have applications in thin film as well as bulk devices.

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Abstract

A single domain wall in a magnetic toroidal cylinder

Department of Physics and Engineering Physics
Morgan State University, Baltimore, MD 21251

One of the major questions driving the research at Morgan State University is "Can one achieve high magnetization (B > 1.7 T) at low fields (H < 1 mT) in iron and iron-cobalt polycrystalline materials, to improve the efficiency of transformers and other related devices?" Current practices in power applications show that there are no materials at present in the market place that can meet these requirements with the required low cost, lightweight and high efficiency ratio. The current possible candidates include Hyperco50 FeCo(2% V) (expensive and hard to use), single crystal iron (impractical), grain oriented silicon steel (low loss overrides cost), amorphous iron alloys (do not compete), polycrystalline silicon iron (cost winner, 1.5T), and nanocrystalline iron (a possibility, however, in the case of cobalt-iron if the anisotropy at the grain boundary of polycrystalline iron were overcome there is a good possibility that the goal of B > 1.7 T) at low fields could be reached. Such an achievement would greatly enhance the efficiency of the power transfer in these devices. A new principle has been found theoretically at Morgan State University that suppresses anisotropy using the geometry of the thin toroid, however we have shown experimentally that the thin film toroid calculations may be applicable to up to millimeter toroids. The results of this investigation are discussed below.

Introduction

One of the major questions driving this research is "Can one achieve high magnetization (B > 1.7 T) at low fields (H < 1 mT) in iron and iron-cobalt polycrystalline materials?" Herzer [1, 2] showed a path toward this goal more 25 years ago. He argued that if the grain size were reduced to below 10 nm, the exchange energy would suppress the adverse effects of magnetocrystalline anisotropy in limiting the magnetization achievable in low fields. Research stimulated by Herzer (about 2000 references to his original paper) has led to new magnetic materials, e.g. nanocrystalline soft magnetic materials, but none of these materials have the desired B>1.7 T at the low fields that would be needed to be better than Goss texture iron silicon used in high performance transformers.

In a program carried out at Virginia State University from 1998-2006, it was found that mechanical milling of iron and iron-cobalt alloys could produce the desired grain size in particles with dimensions of 1-10 microns [3]. In order to make useful magnetic

materials from these particles it was necessary to compact it sufficiently so that voids would be eliminated. The problem is that these particles are mechanically too hard to compact at temperatures lower than the temperature at which grain growth and recrystallization would occur and reduce the effect of exchange to suppress the adverse effects of anisotropy. Further, the work at Virginia State University did not demonstrate that the mechanically hard particles were magnetically soft even though they had the required small grain size.

The work at Morgan State University was originally aimed at finding techniques that would preserve the fine grain size while achieving defect free compaction. In this context the question was also raised about whether the individual particles could be shown to be magnetically soft. If the particles are not already magnetically soft, it is very unlikely that compaction will improve them. As a route to answering this question, it was proposed to turn the individual particles into the shape of a toroid, which would be free from the demagnetizing stray fields of particles that do not have the reentrant geometry of the toroid.

Before fully embarking on the problem of creating the toroid's from particles sintered by a process known as sparked plasma sintering which allows the particles to be rapidly sintered without compromising the nano crystalline particle size, it was deemed necessary to anticipate the magnetic response of such toroids to applied fields that circulate about the hole in the toroid/donut. Fortunately, before actually performing toroid fabrication and measurements, it became possible within the last two years to carry out micromagnetic calculations of the magnetic response of micron-sized toroids.

These questions were addressed theoretically by examining the micromagnetic calculations of the micron-size toroids. From the micromagnetic calculations, it appears that both the exchange interaction at the grain boundaries and the magnetostatic energy are responsible for overcoming the energy reduction that would ensue if the magnetizations were to rotate toward the local anisotropy axes in the grains. As the magnetization rotates away from the phi direction to lower the anisotropy energy, linearly with angle of rotation, both the exchange energy across the grain boundary and magnetostatics charges on the grain boundary both increase with the square of the difference of the angles (that is quadratic) on each side of the grain boundary. The linear term dominates for small angles and rotation takes place, but the magnitude of the quadratic terms is so much larger than that of the linear term, the degree of rotation is slight. If the micromagnetic calculations are carried out leaving out the energy from the magnetic charges at the grain boundaries, every grain rotates to direction of the nearest anisotropy axis. If one then includes the magnetic charges starting from the rotated state, the magnetization rotates back in each grain to recover the pattern where the magnetization is almost parallel to the surfaces. This shows the robustness of suppression

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of anisotropy by the magnetostatics. This new result is of importance to the technology of transformers. To further pursue the micromagnetic consequences of these findings, we also thought to ask the same questions experimentally of the original ferrite core memory toroids that are millimeter-size.

It should be noted however, that in the early 1950's single crystal picture frames were investigate which showed each of the four sections of the picture frame supported a single domain wall that connected with the walls in adjacent sections. These walls were not in stable equilibrium because the energy of the wall decreases as its total length decreases as the walls move toward the inner surfaces of the picture frame. Polycrystalline magnetic toroids were extensively studied as the original core memories. The interest then was in fully reversing the magnetization from one sense of rotation to the opposite. It does not seem that any one inquired into the domain structure in the less than fully magnetized state. Ferrite cores were used because the low magnetic anisotropy did not seem to effect the saturation magnetization or the reversal process. To our knowledge the following questions were never asked: Why the remnant magnetization was so close to the saturation magnetization?, why does the magnetization seem to follow the curvature of the toroid?, or what was the source of the fields that overcame the torques from the anisotropy?

A brief background, in order to study the effects of grain size and grain boundaries on the properties of ferromagnetic toriodal materials and understand why the magnetization seem to follow the curvature of the toroid, we first carried out micromagnetic calculations to model magnetization processes in cylindrical toroids with micron dimensions using a 4 nm grid and then an AC-susceptibility measurements on mm sized toroids was carried out. The micromagnetic calculations showed that a single domain wall can be nucleated through the process of magnetic buckling followed by the formation of a segmented wall with many vortex-anti-vortex pairs which annihilate to leave a clean domain wall with the Néel caps as found by Labonte in his 1968 2D calculations [4]. The process of buckling and wall formation as calculated for a micron size toroid is shown in Figure 1 below for nucleation at the outer radius for a DC magnetic field resulting from a current through the conducting toroid. The frames are labeled by the fractional magnetization with clockwise positive. The Néel caps on the LaBonte wall act as springs against the cylindrical surfaces to account for the stability of the single domain wall.

The important result of these experiments is that the observed behavior of millimeter size toroids can be understood on the basis of the micromagnetic calculations of micron-sized toroids mentioned above. Figure 2 shows the correlation between the Micromagnetic modeling and the AC susceptibility measurements.

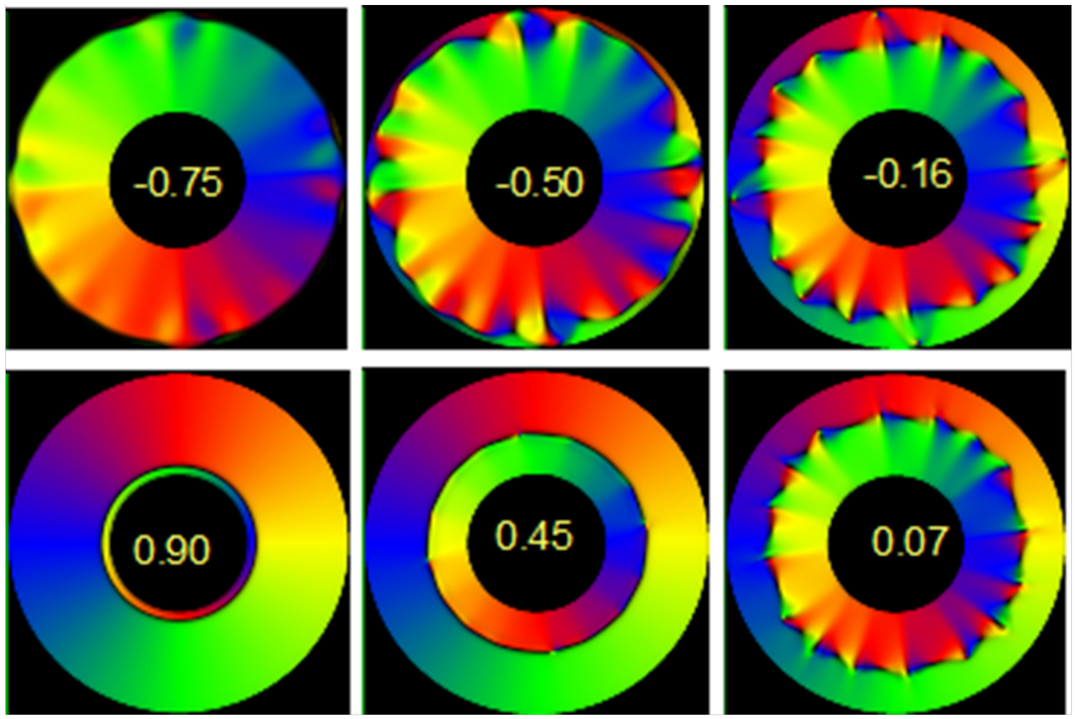


Fig. 1 : The process of buckling and wall formation.

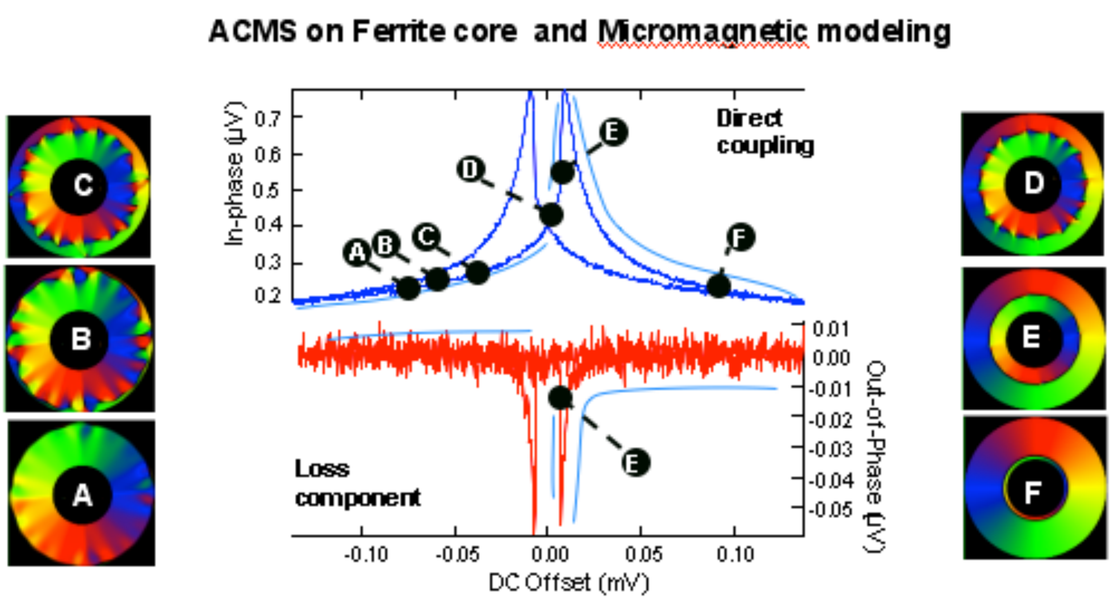


Figure 2. A comparison of the AC susceptibility measurements and the micro magnetic modeling.

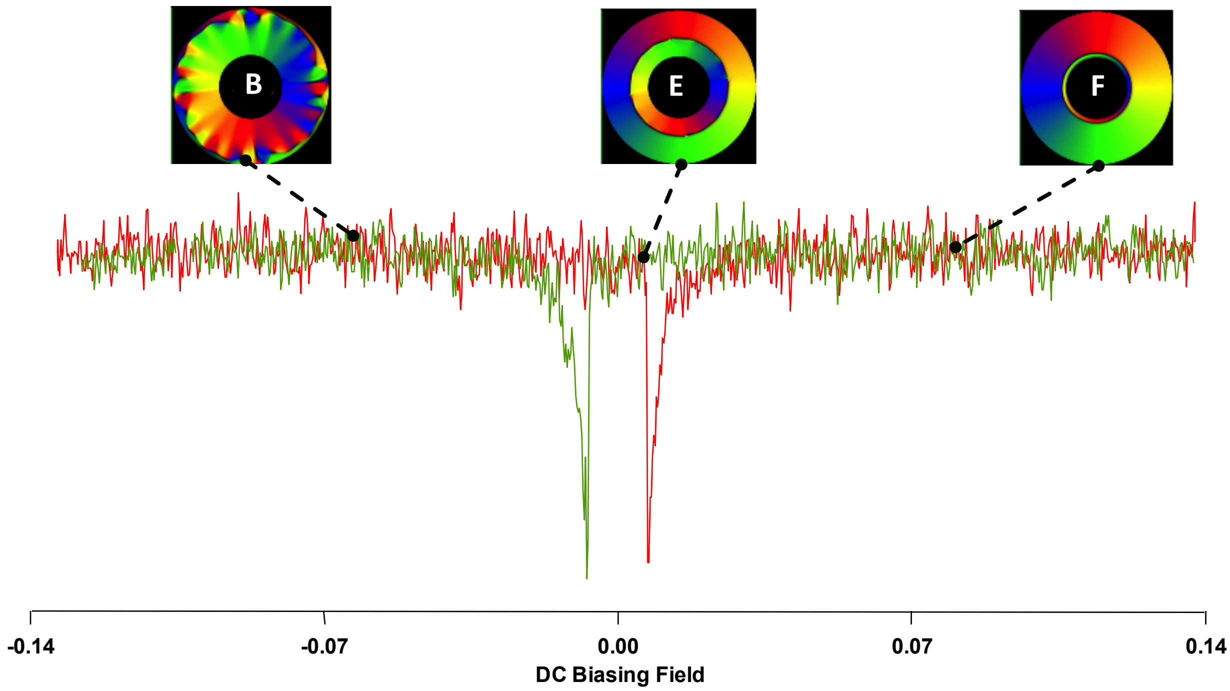
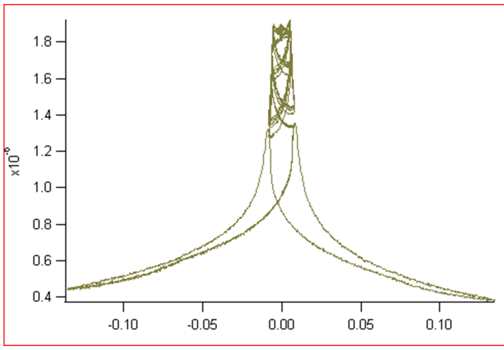


Figure 3. A comparison of the AC susceptibility measurements and the micro magnetic modeling.

AC magnetic susceptibility measurements are probably the most reliable technique for exploring the energy loss associated with magnetization switching. As mentioned above the micromagnetic calculations predict that magnetization switching occurs by the formation of domain walls by a process called buckling. The buckling process is fairly reversible with little or no energy loss (shown at points "A, B, C, and D") in Figure 2 (shown as section "B" in Figure 3, that shows the energy loss as a function of DC bias magnetic field). As long as the DC bias magnetic field does not exceed "E" the magnetization process is reversible. On the other hand at "E" there is well-defined energy loss accompanied by the development of a single domain wall as shown in Figures 2 and 3. As the DC magnetic bias field continues to increase to "F" the magnetization saturates and a single domain structure develops as shown by the micromagnetic calculations. Now as long as the DC bias magnetic field is increased and decreased between "E" and "F" the single domain is preserved and no switching occurs. Figure 4 shows that the susceptibility increases during this process, however an integration of the susceptibility (Figure 5.) shows the saturation magnetization remains constant and the integrated increasing susceptibility (shown as the blue curve) appears to display superparamagnetic behavior.



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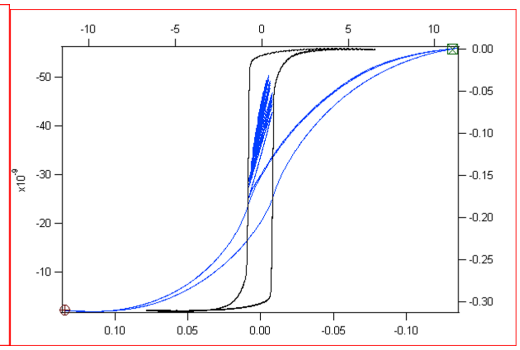

Figure 5.

Future Work

The ultimate goal in this research was to develop a magnetic material to be use in the fabrication of light weight more efficient transformers that could be used in aircrafts, satellites, as well as other commercial applications. However, due to unforeseen circumstances, related to my approximate one-year absence due to illness as well as other issues we were not able to bring this work to an ultimate timely conclusion. The ultimate conclusion entailed the fabrication of a working prototype multilayered high performance toroid transformer to demonstrate the practicality of the work described above.

The micromagnetic calculations and AC susceptibility measurements described above suggest that more efficient transformers may be possible by resorting to multilayered thin film toroids of $CoFe_2$ ($CoFe_2$ is known to have one of the highest saturation magnetizations). However, it should be pointed out that the calculations show that in the thin film toroidal state, the main culprit, the magnetic anisotropy energy can be overcome by controlling the toroid dimensions such that the magnetostatic energy dominates the anisotropy energy, by confining the magnetization to the plane of the toroid. Below we schematically describe the technique will be used to fabricate thin film transformers for circuit board applications.

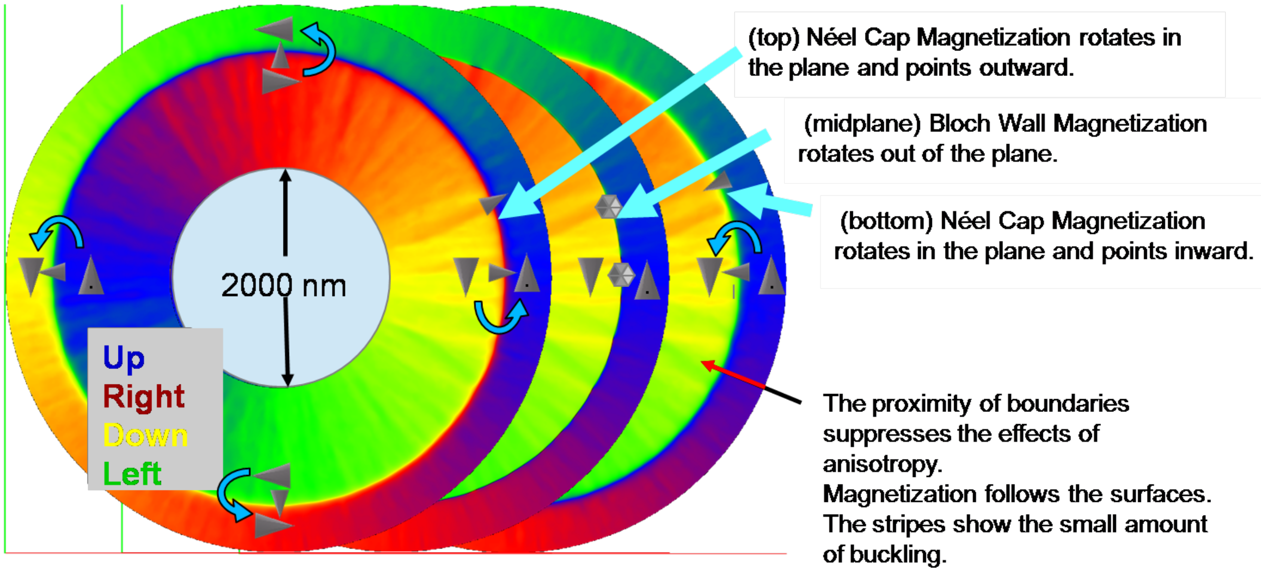

Figure 6.

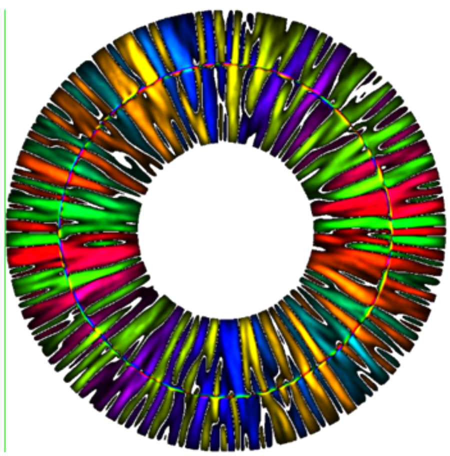

Figure 7.

Deviations from circumferential Direction for the buckling process of magnetization (ripple structure).

The Néel caps are magnetically charged with opposite signs on the two surfaces. When any number of the toroids are stacked on top of one another, a 4 nm gap between them stabilizes the Néel caps and maintains the magnetic structure that suppresses the effects of anisotropy.

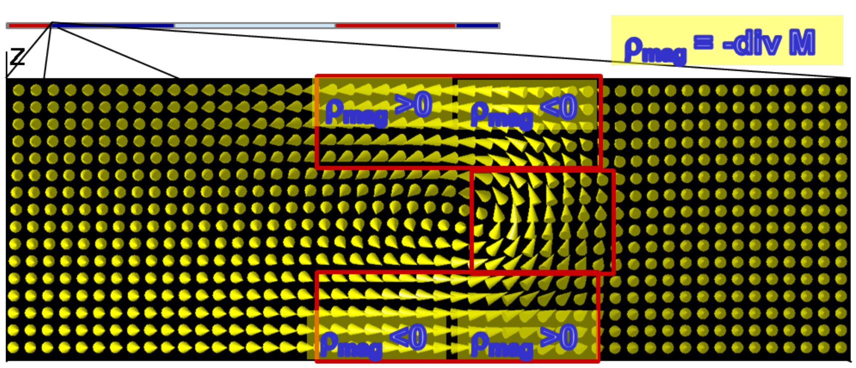

Figure 8. Magnetization in the region of the domain wall with the central Bloch portion capped by Néel portions. Each cone corresponds of a region 4 nm on each side.

In practice, however we had planned to fabricate multilayered toroids of the appropriated dimensions by UHV sputtering. It was learned from the micromagnetic calculations that in toroids with dimensions of 5000 nm OD, 2000 nm ID and less than 300nm thick, magnetostatic interactions keep the magnetization from rotating into the directions preferred by the anisotropy, thereby maintaining the single domain structure. Further, the toroids can be stacked to any thickness provided the gap between them is at least 4 nm. Note that larger diameters may also work, but now the theory is limited by the capacity of the state-of-the- art computers used in the calculations. Further, the experimental results obtained earlier also suggest the toroid transformer idea could possibly be extended to mm-size toriodal donuts.

Shown in Figure 9 is a schematic of a prototype of how we intend to fabricate a thin film multi-layered toriodal transformer with circuit board compatibility. The spiral $CoFe_2$ structure sandwiched between copper primary and secondary spirals and insulating MgO spacers will allow us to fabricate isolators, step-up as well as step down energy efficient thin film toriodal transformers. The fabrication scheme is describe in Figure caption 9.

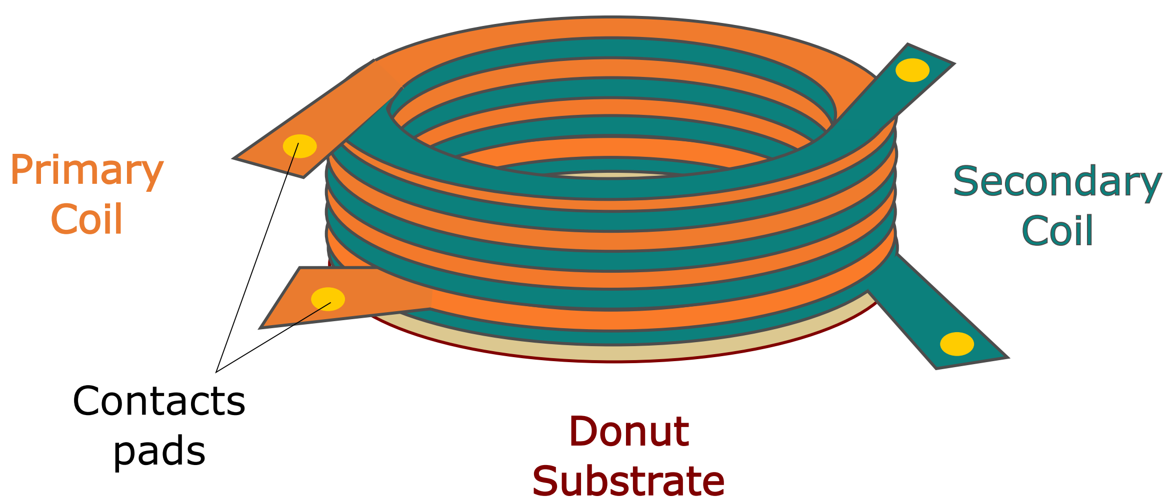

Figure 9. Schematic of stacked and spiral toroids

Configuration of the prototype is shown in the figure above. The two double-donuts, deposited on a ring-shaped substrate, perform the tasks of the primary and secondary coils. The spiral donuts are fabricated by rotating the substrate while the thin film deposited just like the pick-up of a turn-table music player. The contact pads provide the electrical contacts to the starting and end point of a give spiral donut.

It is very unfortunate that time and funding did not afford us the opportunity to bring this investigation to an orderly and productive conclusion. The work as well as the

primilimary results of this investigation represents a tremendous amount of work by all parties involved, Professor Anthony S. Arrott, consultant; Dr. Ezana Neugusee, Post Doc, Conrad Williams, PI, and with more time could have yielded several quality publications. However, in spite of the fact that the grant has ended we plan to salvage what we can in a quality publication!

We would like to sincerely thank AFOSR for granting us the funding to allow us to explore the fertile ideas described in our original proposal.

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Abstract

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